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COMBUSTION PROCESSES IN GRANULAR BEDS
OF SOLID PROPELLANTS

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| → The combustion of granular solid propellants in a mobile bed involves many intricate physicochemical processes, such as heat transfer between gases and solid particles, flow of gas-particle mixtures, heat release resulting from the burning of granular propellants, expansion of the combustion chamber, and fluidization of the granular bed. The main features of these physical processes were simulated by the mobile granular bed combustion (MGBC) model developed at The Pennsylvania State University. This model requires a number | | |

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20. Abstract (Continued)

of empirical correlations as input information. These correlations include: intragranular stress and particle wall friction laws, flow resistance laws for fixed and fluidized beds, convective heat-transfer correlations for both fixed and fluidized regions, and burning rate laws. Numerical computations were conducted using most realistic correlations available in the literature. Theoretical results have been compared with experimental data for both live and inert propellant grains. In the live propellant case, tests were performed in a simulated 30 caliber system. In the inert propellant case, the particle displacement, porosity distributions and pressure-time traces were obtained through the use of a transparent combustion chamber with a high-speed motion picture system and a set of high-frequency pressure transducers. The close agreement between theoretical and experimental results showed good predictability of the MGBC model.

STATEMENT OF PROBLEM STUDIED

The overall objective of the research program was to advance the state-of-the-art in the knowledge of combustion processes in a granular propellant bed by obtaining the necessary empirical correlations for theoretical model validation.

The work involved the following studies:

1. The intragranular stress and particle-wall friction measurements and correlations in granular propellant beds;
2. Transient compaction processes in granular bed caused by percussion primers;
3. Boundary condition specification for predicting combustion processes in mobile granular propellant beds;
4. Characterization of mass flow rate for various percussion primers; and
5. Model validation by comparing theoretical results obtained from mobile granular bed combustion (MGBC) model with test firing data using live and inert granular propellants.

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SUMMARY AND CONCLUSIONS

1. Intragranular Stress and Particle-Wall Friction Study:

Correlations for intragranular stress, particle-wall friction, and speed of sound transmitted through aggregates of granular propellants are necessary as physical input functions for predictive theories in interior ballistic cycle studies. A test rig was designed for obtaining instantaneous porosity, intragranular stress, and particle-wall friction in the mechanical compaction of granular material. A dimensionless compaction similarity parameter was found to correlate the experimental data well, regardless of particle size and shape. Empirical correlations for WC-870 and WC-846 granular propellants were obtained. Mathematical expressions for the speed of sound transmitted through these two types of propellants were also obtained. A scanning electron microscope was used to examine some of the deformed granular propellants after compaction. Numerous surface fissures were observed; these increased surface areas may contribute significantly to the DDT process.

2. Transient Compaction Study:

Transient compaction of granular propellant bed caused by venting of a primer blast can greatly alter the initial porosity distribution in a granular bed and result in an ullage space near the primer exit. As a result of porosity change and ullage generation, there is a substantial decrease in both gas permeability and penetration depth of primer products

into the bed. Thus, the consecutive flame spreading and combustion process are remarkably affected. Investigation of this transient compaction process was conducted both theoretically and experimentally. To facilitate viewing, inert granular particles were painted section by section with fluorescent paints and loaded into a transparent plexiglass chamber. The transient compaction process was then filmed with a high-speed photography system with a framing rate at 44,000 pictures/sec. Pressure-time traces at various locations of the bed were also recorded. Experimental data were compared with predictions of the Mobile Granular Bed Combustion (MGBC) model. Good agreement between theoretical and experimental results further supports the validity of the MGBC model.

3. Boundary Specification:

In the modeling of transient one-dimensional, two-phase combustion of granular propellants in gun interior ballistics, the boundary conditions at both the breech end and the base of the projectile must be adequately specified. It was found that these boundary conditions can significantly influence numerical solutions. The form and the total number of the boundary conditions required depend upon the relative velocities of the gases and solid particles with respect to the solid boundary and the condition of fluidization. In the study of a simulated gun system, the flow properties at the boundary are obtained by considering (1) the local balances of mass, momentum, and energy over a small control volume adjacent to the boundary, (2) the compatibility relationships along the characteristic lines, and (3) a number of relationships

according to the instantaneous flow conditions. These considerations are necessary to provide the extraneous boundary conditions required for solving the partial differential equations with a second-order numerical scheme. Numerical results were compared and found in agreement with test-firing data.

4. Characterization of Mass Flow Rate:

Percussion primers have been used widely for ignition in various propulsion systems. However, the mass and energy fluxes generated through a primer blast are strongly time dependent, and are not well characterized. It has been observed that the ignition and flame spreading processes of solid propellants greatly depend upon the primer output. Therefore, the objective of this study is to determine the instantaneous gaseous mass flow rate, the energy fluxes, and the percentage of product in the condensed phases. A test rig has been constructed to conduct primer characterization studies. A theoretical model based upon two-phase conservation equations has been developed. The gaseous mass flow rates for a number of primers have been obtained from the theoretical model which uses the recorded P-t traces, and the adiabatic flame temperature based upon thermochemistry calculations. Experimentally, good reproducibility in the up-rising portion of the P-t traces has been observed. The instantaneous gases mass flow rates for two different percussion primers have been obtained. Results also indicate significant percentages (~40%) of product in the condensed phases. The potential importance of the condensed phase product to the ignition mechanism suggests the need for further study.

5. Model Validation:

The combustion of granular solid propellants in a mobile bed involves many intricate physicochemical processes, such as heat transfer between gases and solid particles, flow of gas-particle mixtures, heat release resulting from the burning of granular propellants, expansion of the combustion chamber, and fluidization of the granular bed. The main features of these physical processes were simulated by the mobile granular bed combustion (MGBC) model developed at The Pennsylvania State University. This model requires a number of empirical correlations as input information. These correlations include: intra-granular stress and particle wall friction laws, flow resistance laws for fixed and fluidized beds, convective heat-transfer correlations for both fixed and fluidized regions, and burning rate laws. Numerical computations were conducted using most realistic correlations available in the literature. Theoretical results have been compared with experimental data for both live and inert propellant grains. In the live propellant case, tests were performed in a simulated 30 caliber system. In the inert propellant case, the particle displacement porosity distributions and pressure-time traces were obtained through the use of a transparent combustion chamber and a high-speed motion picture system and a set of high-frequency pressure transducers. The close agreement between theoretical and experimental results showed good predictability of the MGBC model.

PUBLICATIONS

The papers and reports, representing the results obtained through the sponsorship of this program, which were published, accepted for publication or presented are listed below.

1. Kuo, K. K., Yang, V., and Moore, B. B., "Intragranular Stress, Particle Wall Friction and Speed of Sound in Granular Propellant Beds," Journal of Ballistics, Vol. 4, No. 1., January 1980, pp. 697-730.
2. Yang, V. and Kuo, K. K., "Transient Compaction Processes in Granular Beds Caused by Venting of Primer Products," CPIA publications 329, 17th JANNAF Combustion Meeting, Vol. II, November 1980, pp. 23-43.
3. Chen, D. Y. and Kuo, K. K., "Boundary Condition Treatment of Transient Two Phase Flows in Gun Systems," AIAA Paper No. 80-0080, AIAA 18th Aerospace Sciences Meeting, January 14-16, 1980, Pasadena, California.
4. Chen, D. Y., Yang, V. and Kuo, K. K., "Boundary Condition Specification for Predicting Combustion Processes in Mobile Granular Propellant Beds," accepted for publication in AIAA Journal, 1981.
5. Kuo, K. K., Moore, B. B. and Chen, D. Y., "Characterization of Mass Flow Rates for Various Percussion Primers," presented at Seventh ICOGER Conference, Gottingen, Germany, August 20-24, 1979. Also accepted for publication in the Progress Series of AIAA 1981.
6. Kuo, K. K., "Comparison of Theoretical Results Obtained from Mobile Granular Bed Combustion Model with Test Firing Data Using Live and Inert Granular Propellants," presented at ARO Workshop on Multi-phase Flow, February 2-4, 1981, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland.
7. Moore, B. B., "Characterization of Various Primers and Determination of Intragranular Stress Within a Compacting Granular Bed," M.S. Thesis, Department of Mechanical Engineering, The Pennsylvania State University, 1979.
8. Chen, D. Y., "Transient Mobile Granular Bed Combustion of Solid Propellants with Moving Boundary," M.S. Thesis, Department of Mechanical Engineering, The Pennsylvania State University, 1979.
9. Yang, V., "Compaction of Particles in Granular Propellant Beds by Mechanical and Gas Dynamic Loadings," M.S. Thesis, Department of Mechanical Engineering, The Pennsylvania State University, 1979.

PARTICIPATING SCIENTIFIC PERSONNEL

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